TOWARDS MASTER DATA MANAGEMENT FOR CULTURAL HERITAGE: THE SACRI MONTI WEB PLATFORM

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Commission II

KEYWORDS: 3D, Point Cloud, Cultural Heritage management, Information System, Web Platform, Master Data Management

ABSTRACT

This paper focuses on managing the Cultural Heritage maintenance process through web platforms, exploring a data-driven new approach that relies on the framework of Master Data Management (MDM). The MDM framework is based on data quality, revisioning and auditing of information, and the Microsoft SQL Server Master Data Services (MDS) was used. It is a highly customizable commercial tool that proved to be effective and able to manage extended and articulated databases and provide stability and long-term software support. MDS provides powerful tools to avoid duplicates, ensure data quality, and record all the modifications that occurred on the dataset over time. These are key features to build a reliable platform for information management of complex CH assets.
The paper presents some first tests applied for the Sacri Monti of Piedmont and Lombardy case of study. It is a UNESCO wide religious architectural complex site in northern Italy's mountainous part. The paper compares approaches and previous experiences of Sacri Monti management using web platform information systems, such as the BIM3DSG, Chimera, and Main10ance, to support Sacri Monti management activity.

1. INTRODUCTION

The digitisation projects of Cultural Heritage (CH) require thorough planning, accurate implementation, and constant supervision in the operational phases. The digitisation project concerns not only the CH asset but also all the related information useful to its description and requires preparation of the maintenance and protection activities. The digitized data must be managed to be accessible and stable over time.
The recent evolution of survey techniques and tools allows operators to capture and process a considerable volume of data easily and quickly, with unprecedented detail, precision, and reliability. Integrating different survey sensors maximizes the possibilities of digitizing the built heritage, increasing the amount and the quality of the information acquired. The significant possibilities of documenting CH with complete, fast, and eventually repetitive surveys stress the need to manage the data produced flexibly, rigorously, and resiliently. The capture of dimensional data is frequently conducted with the acquisition of information concerning the building materials, their state of conservation and the description of the ongoing and future activities. These heterogeneous data can be natively digital or one of the products of a digitization campaign of analogue ones. They help track the condition and interventions that occurred on the CH asset.
The amount of data produced in CH documentation significantly increases the need for complete tool to visualize and efficiently use the 3D data by all the sector operators for different purposes. This latter consideration stresses the need for flexible tools to easily share data and empower inspection, maintenance, and restoration processes.
Presently, the web platforms for 3D data visualization and information management represent a promising solution for accessing and sharing the data related to CH (Fassi et al., 2023).
A web platform is a Web App developed to view and interact with 3D representations, such as models, meshes, and point clouds, that can be stored in the system or uploaded by the user.
The web platforms available in the market generally offer efficient tools for 3D data visualization and annotation but usually do not provide specific instruments to structure all the data related to the CH and its maintenance (Fiorillo and Spettu, 2023).
Over the years, numerous attempts have been made to introduce techniques from different application domains and adapt them to create 3D information systems tailored to CH's realm. The experiences that employed BIM systems might be listed among them. These attempts are directed towards the issue of organising the CH asset into objects and connecting them to Information Systems (IS). However, they fall short of addressing the necessity to model and significantly simplify the representation of the asset, particularly considering the lack of information systems that are typically CH-adaptable or, at the very least, readily customizable to various scenarios (García-Valldecabres et al., 2021; Lovell et al., 2023; Yang et al., 2020).
It is important to ensure that digital data are correctly archived, accessible and related to proper metadata (Maravelakis et al., 2013) that empowers the understanding of methods and technologies used to produce them. The data management activities must be extended to any type of information, independent of its origin and source.
So, giving a reliable structure to the whole digitisation products (3D data and info) that has to be rigorous, easy to access and stable through time is not a simple task, and the challenge is doing this allowing a flexible custumizable structure that must be adapted case by case, must be easy to access and stable through time.

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Figure 1. Images of the restored Chapel I of Sacro Monte of Orta "The birth of Saint Francis of Assisi". The restoration regarded the exterior and interior surfaces and decorative apparatus (Ente di gestione dei Sacri Monti, 2024a).

This presented research attempts to solve these challenges, testing systems that make data consistency and customization flexibility their strong point as the Master Data Management (MDM) tool. It is a *"technology-enabled discipline in which business and information technology work together to ensure the uniformity, accuracy, stewardship, semantic consistency and accountability of the enterprise's official shared master data assets."* (Gartner Inc, 2023; Stedman and Vaughan, 2023).
This article presents the case study of the informative web platform for the periodic inspection and maintenance of the Sacri Monti, following a Master Data Management approach to address the data-structure problem to overcome the main limitation of the available web platforms in terms of information management.

2. THE SACRI MONTI CASE STUDY

The Sacri Monti is a complex of nine devotional paths between the Italian regions of Piedmont and Lombardy. Each *Sacro Monte* is built on the top of a hill and is articulated as a sequence of chapels in which stories about Christianity and the Gospels are visually narrated. Visual storytelling is constituted by frescoes, pictures, and realistic statues realized between XV and XIX centuries by some eminent artists of the north of Italy (Figure 1). Each *Sacro Monte* has a significant religious and symbolic value and represents a peculiar example of the integration of devotional architecture and mountainous landscape, as well as houses valuable statues and frescos inside the chapels. For these reasons, UNESCO added the Sacri Monti of Piedmont and Lombardy to the World Heritage List in 2003 (Ente di gestione dei Sacri Monti, 2024b; UNESCO, 2023)
The peculiar condition of Sacri Monti in terms of geographical collocation and architectural features requires a multi-scale approach both for the maintenance activities and the information management system. The complex is articulated in different locations, and each *Sacro Monte* has several chapels that host various narrative elements (architectural ones, pictures, statues...) that are the object of the inspection and restoration activities, as well as the structures that protect the integrity of the decoration apparatus, as roofs as walls (Achille et al., 2019; Ente di gestione dei Sacri Monti, 2024a).
A multi-sensor, repeated survey of the Sacro Monte of Domodossola was carried out as the main topic of the summer school "Laboratory of Places – history, survey, evolution" in the 2018 and 2019 editions. The survey was done with Terrestrial Laser Scanner (TLS), close-range and UAV photogrammetry, Mobile Mapping System (MMS) and total station for correct referencing and accuracy assessment. The result is the point cloud of the chapels, interior and exterior, suitable for the 1:50 representation scale and referenced into the topography and landscape. The point cloud was used to produce BIM models, CAD drawings, orthophotos and mapping of materials and decay (Achille et al., 2019).
The outcomes of the survey campaign are at disposal of the Ente di Gestione, which over the years has also collected other data from digitization campaigns carried out for research or educational purposes (Zerbinatti et al., 2023, 2021).

2.1.1 Experiences and evolution of Sacri Monti platforms

To support planned and extraordinary CH asset maintenance, the *Ente di Gestione dei Sacri Monti* tested several methods for its data management. The primary need concerned the possibility of accessing and editing data without any specific software and limiting the data post-processing by *Ente* operators.

2.1.2 The BIM3DSG and Chimera platforms

Starting in 2017, a web platform based on open-source modules was developed and tailored on the Sacri Monti needs. The BIM3DSG platform (Fassi et al., 2015) was developed to provide an effective tool to support the inspection, maintenance and reporting process, keeping a centralized archive of all the information referenced on the 3D model.
The development of the platform started from the consideration that it is necessary to rely on the collaboration of different professional figures with their heterogeneous background and competencies to manage such an articulated CH complex. Typically, each of these people is accustomed to using specialised software and technology that serve to the specific requirements of their field. Developing a web-based information system for data management that is compatible with any hardware and software allows for the creation of a centralised and regularly updated tool. This tool facilitates collaboration and the sharing of essential data among the individuals participating in the process.
From this consideration, the development of BIM3DSG was oriented towards the form of a web platform, accessible through the internet, hardware and software independent, as the only technical requirements are an internet connection and a web browser. The choice aims to increase the accessibility level of the data as it is considered a critical aspect. The web-based approach natively allows data centralisation and enables every user to access the most updated and unique version of the information (Achille et al., 2019; Tommasi et al., 2020).
The platform was built based on open-source modules and libraries in order to reduce ownership costs and have more customization possibilities. The relational database is based on PostgreSQL (PostgreSQL Global Development Group, 2024), managed through PGAdmin (PostgreSQL Community, 2024).
The database is structured to recall the semantic subdivision of the heritage assets according to the working practices used by the management of Sacri Monti. The structure that proved to be the most adaptable is a 4+1 one that uses four layers to organize the whole object (Achille et al., 2019). The 3D model to be used in the platform are in different formats: they can derive from the multi-sensor survey campaign or be realized by the technical

office of *Ente di Gestione dei Sacri Monti*, relying on the already available on their archive CAD or paper drawings when the 3D survey was not available, using Autodesk Revit (Autodesk, 2023). The BIM method for the geometry production was chosen because of the object-oriented approach natively adopted by the BIM modelling software, which produces a separate object for each architectural element, following the logical structure adopted for the specific case, choosing which elements to model, which ones to simplify and how they fit into the logical structure of the database. As the platform is software agnostic, the 3D models can be realized also in other 3D software instead of the BIM ones, as the platform supports the OBJ format. The information database supporting the maintenance activities is structured in different entities that serve specific purposes. The "object" is the "digital image" of the physical architectural asset, and each object can have different "versions" and "subversions". These two are critical for the maintenance process as they can keep track of the modifications that intervened on the real object. A modification can be a damage, an inspection, a maintenance activity or the acquisition of new data, including surveys. A new version is when an object is also modified physically, which implies a change in its 3D representation. A subversion is a modification only related to the information connected to the object or the physical modification of the asset without new models to represent it (Achille et al., 2019; Rechichi, 2020).

The versioning and subversioning of the objects are triggered by the "intervention" event, which represents an action or a modification in the real world that requires an update at some level of the database, as described previously. The BIM3DSG web platform proved to be an effective tool to access and manage data through the web. The main limitation can be identified in the lack of support for the point cloud, commonly requested in the reality capture process. For this reason, is required to model on the chosen software new geometries for each update. In the case of reality-based modelling, this operation can be considerably time-consuming and requires an interpretation phase for the most challenging shapes, which might introduce differences and errors from the data source (Achille et al., 2019). In 2019 the platform was updated into a new version, Chimera (Bruno et al., 2020; Rechichi, 2020), that adopted a new multi-scalar BIM+GIS approach particularly suitable to the Sacri Monti case study. Moreover, Chimera has overcome some limitations in the web-visualization interface, making the visualization of the information system more transparent and more appealing. The user interface was re-designed in order to be clearer, easier and suitable for the use on recent digital devices.

Moreover, the floating window feature was implemented, allowing users to freely arrange panels inside the browser window. The rendering performance are significant, thanks to the use of seven graphical LOD that are automatically computed by the system on the loading phase, and to the implemented caching mechanism (Rechichi, 2020). Chimera combined the BIM and GIS tools as two different ways to access a unique repository of information, as it is required in the Cultural Heritage cases that need to be managed at different levels, combining a specific approach to the single architectural element to the general management of the asset as a whole.

This could be the case with archaeological sites or articulated and scattered architectural complexes such as the *Sacri Monti*. Moreover, this latter case is peculiar because of the presence of nine different *Sacri Monti*, and because the single *Sacro Monte* is articulated into several chapels distributed along the devotional path. The GIS tools are implemented through the PostGIS (PostGIS PSC, 2024) libraries and manage the most common geospatial entities as vectors, raster both as uploaded into the platform or loaded through the GeoServer framework (Open Source Geospatial Foundation, 2024).

2.1.3 The Main10ance platform

Main10ance (Colucci et al., 2023; Main10ance, 2023) is a multi-purpose platform developed to support the programmed maintenance and management of Cultural Heritage complexes with a multi-scale, BIM+GIS approach. The platform was developed inside an EU Interreg Italy-Suisse project from 2020 to 2022. Main10ance aims to simplify gathering, archiving, interacting and visualizing information relevant to CH management and fruition. The platform is operative online and accessible through a dedicated website (Main10ance, 2024).

The platform's pilot project that aims to be generalizable and scalable to any CH application concerns the Sacri Monti as a complex with a specific focus on the ones of Varallo, Orta and Ghiffa. For the Sacro Monte of Varallo, a complete 3D survey suitable for the 1:100 representation scale was conducted with a multi-sensor approach (Matrone et al., 2023), obtaining as final products the digital model of the terrain and the point clouds of the chapels. The implementation of the Level of Detail (LoD) into the platform is crucial to understand its functioning, as it determines the visualization scale of the object, the available information, the modelling strategy and, consequently, which interface on the platform will be used and which kind of user is able to access to the data.

LoDs from 0 and 1 are dedicated to the regional scale and to the whole Sacri Monti system. LoD 2 is a 3D model of the single *Sacro Monte* with the buildings modelled as their external shapes, the terrain surface and the pathways. LoD 3 represents the single building (e.g. a specific chapel) with the architectural elements composing it. The LoD 4 represents through images or external links the architectural elements or part of them that were chosen not to be modelled. Moreover, a LoD 5 was introduced to represent the information in the restoration database.

The modelling part at the single *Sacro Monte* scale (LoD 2 and 3) is performed inside the Autodesk Revit software starting from the imported point cloud data. The object-oriented modelling approach produces models already structured into constitutive architectural elements, although due to the software intrinsic limitations, some architectural elements are not represented by BIM software, and models are not labelled correctly (Matrone et al., 2023). The platform uses an alphanumeric identifier that contains all four layers of collocation (e.g. *Sacro Monte*, building, element type, element code), that attributes the models to the proper category, overcoming the problem described previously. Main10ance uses three different visualization modules according to the LoD considered: the active user and the operational purposes. The first one is the GIS viewer, which locates the CH assets on a base map and can display layers from the territorial geospatial databases.

The second interface is the BIM viewer, based on the Application Programming Interface (API) of Autodesk Platform Services, formerly known as "Forge" (Autodesk, 2024), to display and interact with models at the LoD 2 and 3. This interface allows navigating the 3D model, sectioning the geometries and visualising the architectural elements' information through properties panels. The third interface is the Artifact Viewer, which shows the LoD 4 elements as images or attached files in a gallery.

The authorized users are provided with planning and scheduling interfaces for the maintenance cycle. The maintenance cycle is structured into four phases, represented into an equal number of tabs. Planning and Programming tabs are accessible only to site managers and allow to decide the frequency and schedule of inspections and assign the task to specific operators, that will find it into the Execution tab. The History tab act as the archive of the past operations. Managers have at disposal also a résumé of the operations through a dashboard.

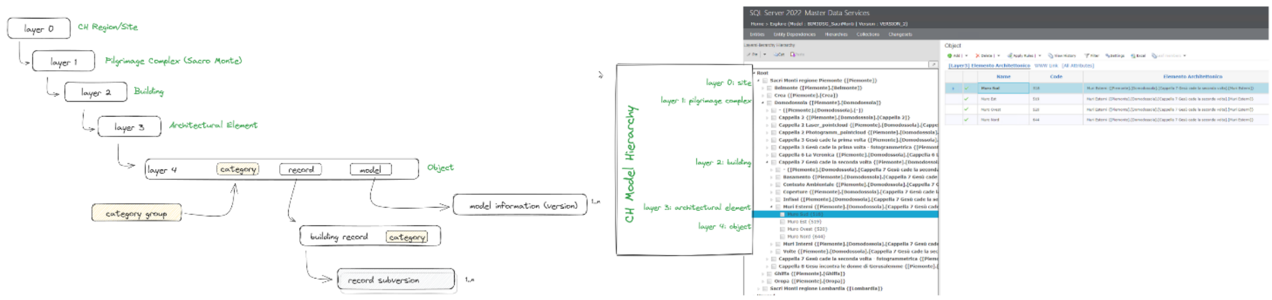

Figure 2. Left: The breakdown structure in 4+1 layers was adopted for the case of Sacri Monti in the BIM3DSG System. Right: the implementation of the structure in the MDS database.

2.2 Open issues and possible developments

Each previously presented approach and solution solves several problems but inevitably introduces limitations. A web platform for CH can be seen as the balance between the nature of the maintenance process for the CH asset, the digitization needs, and the technological and material resources available for operations. As a working tool, the platform needs its own maintenance at the database and software level. On this topic, it is relevant to consider that on the side of resources, a platform based on open-source modules can reduce the software component ownership costs but might increase the need for maintenance for updating the software and keep the system efficient. Moreover, the possibility that the used component or library might be discontinued or not updated by the open-source community must be considered. On the other side, commercial components usually ensure longer-term support and more stability, but this comes at a higher price.

The modelling phase is undoubtedly time-consuming if carried out with manual methods, a reality-based approach, and high accuracy (Acosta et al., 2022; Spettu et al., 2021). A possible solution is using the point clouds as the geometrical basis. This aspect is of significant interest, and it is addressed by many commercial platforms that propose advanced point cloud visualization and sharing (Cintoo, 2024; Geovast 3D, 2024). Despite the recent developments and increase in the offer, most of the available commercial platforms are efficient in the "geometric model" rendering part. However, at present, they offer only very basic tools for annotation, not enough for the professional practice inside management processes in the CH field (Fiorillo and Spettu, 2023).

Moreover, point clouds, as products of the three-dimensional survey, are a raw and undifferentiated accurate geometrical representation of the architectural and landscape shape. The use of point clouds inside a structured database that represents the logical breakdown of a CH asset seen from the restoration perspective requires preliminary work of cleaning and classification that can be done manually, semi-automatically or automatically according to the chosen methods and the complexity of the case (Teruggi and Fassi, 2021; Zhang et al., 2022). The approach based on BIM prioritizes the use of 3D models with semantic structure, which serve as a foundation for the linked information. Within the domain of CH, there are instances where, due to constraints in time, expertise, and resources, models and visual representations are not feasible to reconstruct or iterate. However, maintaining up-to-date information is crucial for day-to-day management as it reflects the current condition of the CH asset. Additionally, it is often simpler and more time-efficient to update a database rather than to adjust geometrical data or to merge existing data with new surveys.

This research investigates the feasibility of inverting the conventional BIM process of appending information to geometry. It explores the concept of orienting the CH information system around the essential core data required for its management, which may be supplemented with comprehensive metadata and entity attributes, and subsequently visualizing this information via 3D geometrical representation.

3. THE MASTER DATA MANAGEMENT APPROACH

This paper proposes a novel approach to developing web platforms for Cultural Heritage management, inspired by the principles of Master Data Management and using its specifically developed tools.

Gartner defines Master Data Management as a "technology-enabled discipline in which business and IT work together to ensure the uniformity, accuracy, stewardship, semantic consistency and accountability of the enterprise official shared master data assets. Master data is the consistent and uniform set of identifiers and extended attributes that describes the core entities of the enterprise including customers, prospects, citizens, suppliers, sites, hierarchies and chart of accounts" (Gartner Inc, 2023). More in detail, the MDM is the discipline that defines the most critical data within an enterprise or organization and their policy. The Master Dataset is usually a subset of all the managed data and is available across the organization. The creation of the Master Dataset starts with its cleaning and systematization, as it must be unambiguous, lean and without duplicates. The maintenance of the Master Dataset is ensured by the Data Governance policy of the organization, which is meant to ensure the long-term efficiency and consistency of the dataset, as the success of the MDM strategy is closely related to the quality of the data (Fleckenstein and Fellows, 2018).

The objective of establishing a Master Data Management (MDM) Data Hub, which serves as a System of Records, is to orchestrate the central database holding the master data in such a way that it remains synchronized with the source system feeding the Data Hub, and satellite systems integrated downstream consuming this data. A Data Hub is an approach to efficiently managing the access and sharing of data. Systems that connect to the Data Hub send and receive data in real-time, as it acts as a centre of distribution (Lauer, 2021).

The synchronization aspect is crucial as these systems use, consume, and enrich the master data, forming a complex data ecosystem within the institution involved in preserving cultural heritage items.

The MDM Data Hub is designed to monitor all recognized attributes within the operational scope of the organization or the institution. It is tasked with creating and maintaining different versions of each data model, capturing the evolution of data over various timeframes. However, these versions are only committed to the master record after a stringent process that includes thorough validation, necessary approvals, and compliance with established quality rules. This ensures data integrity and trustworthiness.

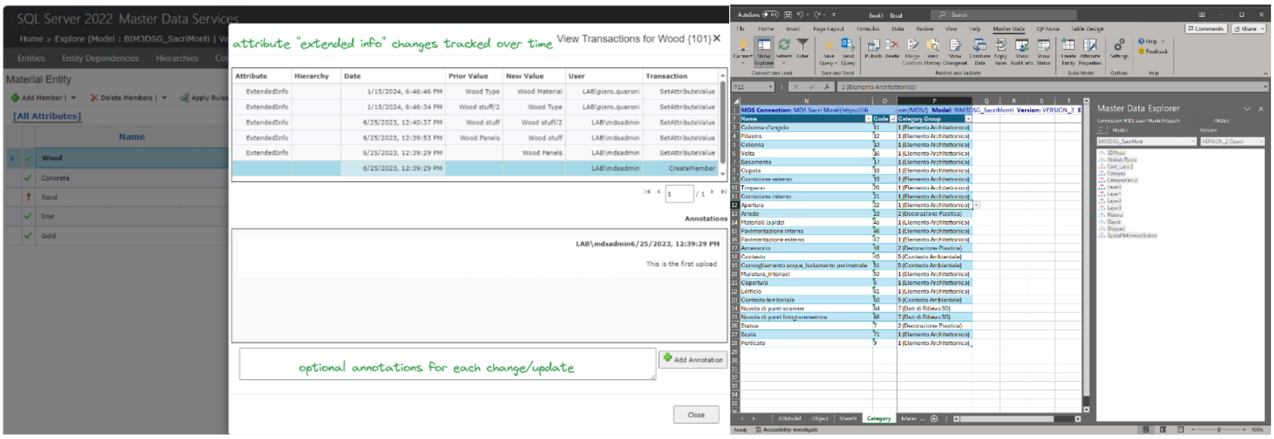

Figure 3. The user interface of MDS. On the left is the version management tool for the data structure on the web. On the right is the Excel add-in for data insertion.

The hallmark of this system is that it is subject-oriented, meaning it is organized around subjects of data (artefacts, conservation records, digital assets, etc.) rather than processes or departments. It is integrated, implying seamless interaction with and among various data sources and applications. Its time-varying nature allows for the historical tracking of data changes, providing a temporal perspective on data evolution. Moreover, the hub is non-volatile: once entered the system, data is stable and remains unaltered until intentionally revised, providing a reliable audit trail.

This cohesive approach aims to achieve what is often called “one version of the truth” within the organization. It’s a unified and agreed-upon view of accurate, comprehensive data and, most importantly, universally recognized as the single source of truth. This foundational concept is pivotal, as it enables consistent decision-making and operational processes across the entire organization, preventing the discrepancies and fragmentation that can arise from multiple versions of data residing in disparate systems. The role of MDM Data Hub, transcends mere data storage, becoming a critical facilitator of organizational coherence and reliability in data-driven strategies.

The key role of a Data Steward, typically held by a Subject Matter Expert (SME) who may not necessarily have a background in Information Technology, is pivotal in managing the integrity and usability of data within an organization. The crux of Data Steward responsibility lies in maintaining and curating data elements within a metadata registry. The steward toolkit can vary depending on organizational needs but often includes web-based applications and add-ins to spreadsheet editors like Microsoft Excel. These tools enable the steward to create and edit data models, establish and refine hierarchies, and formulate business rules that govern the use and handling of data.

The role of the steward involves a continuous cycle of running, processing, and validating data to ensure that improvements are made iteratively. This cyclical process is crucial for adapting to data use changes and responding to the evolving CH needs.

The Data Steward is in charge of upholding high data quality. This encompasses the data accuracy, completeness, reliability, and relevance, ensuring it meets the strict standards for decision-making and operational processes. The Data Steward acts as a “guardian” of data quality, ensuring that the organization’s data assets remain trustworthy and valuable.

3.1 MDM tool: Master Data Services

The newly designed system is built upon the robust framework of Microsoft SQL Server Master Data Services (MDS), a comprehensive master data management solution engineered by Microsoft for the organization of relational databases (Microsoft, 2023). The system leverages the MDS advanced toolset to facilitate precise structuring and association of master data, customized to accommodate the complex, multifaceted requirements of the Sacri Monti Management Office. The system’s design strategically centralizes the architectural element, streamlining it as the focal point for all ensuing maintenance actions and protocols, thereby enhancing operational efficiency and data coherence.

MDS is typically used by organizations that need for maintaining consistency across their data estate, providing access to the most current and accurate version of master data and enforcing the paradigm of the “single version of the truth”. It is a powerful tool for data stewards and IT professionals who manage and maintain the integrity of mission-critical data.

MDS is based on a model-driven architecture where the data model dictates the stored data structure. A model can be thought of as a container for the master data and can include multiple entities, which are like tables in a relational database. An entity represents a type of master data, such as “Material” or “Building”, and is made up of attributes that, like columns in a table, define the data stored in an entity. Hierarchies and collections can be defined to organize and group data within entities, which is especially useful for searching, reporting, and analysing data. MDS allows the definition and enforcement of business rules to ensure data integrity and quality against specific constraints. These rules can be used to validate data when entered into the system, ensuring compliance with industry processes and requirements. It also supports versioning of the master data. This allows for managing and viewing data as it changes over time, which is critical for auditing, lineage and historical analysis. MDS can integrate with other systems via multiple interfaces. This allows data flow into and out of MDS from various sources and satellite systems. On the security side, several features are included to control access to the master data based on user roles. This ensures that only authorized accounts can add, view, or modify the master data.

Users can interact with the Master Data as tables using standalone software or the web-based interface. MSD provide an add-in for Microsoft Excel that allows one to manage Master Data directly from the software, which is a familiar environment for many users. Moreover, MDS features a web-based interface where users can perform various tasks such as creating models, managing data, and applying business rules. The web-based interface can be accessed through different devices, including mobile ones. Before any changes are committed to the database, MDS allows the data to be validated and any issues to be addressed. Once the data is validated, it can be published, becoming the "golden record" for master data. MDS also provides the so-called "Subscription Views", which are database views that provide a read-only, near real-time feed of master data to subscribing systems and applications. For all the previous considerations, the authors see MDS as a suitable and effective tool for building an information system dedicated to the programmed maintenance of CH. MDS is a commercial framework produced by a well-established company and is largely adopted in several fields and at any scale of data management. This aspect can ensure long-term support and stability during the development and use phase. The features described before are considered adequate for the task at hand and can support any CH asset's maintenance processes with every level of complexity if the adopted data structure and data governance policy are solid.

4. IMPLEMENTING MDM ON CH

The new platform development for the Sacri Monti started reconsidering the data structures constructed for the previous BIM3DSG platform, adapting, modifying, and implementing them inside the new system and with new paradigms. The value of this approach lies in using the most general available tools for data management and related methods to address the problem of Cultural Heritage data fruition, finding powerful tools and solutions that are easy to maintain at the software level and ensuring long-term support and compatibility. Moreover, considering the lesson learned from the BIM3DSG, the new platform has to be adaptable to multiple data sources but ensure at the same time that the input requirements are fulfilled. The envisioned MDM system serves as a rich framework for cataloguing and preserving the CH assets and their related information. Following the MDS model-driven approach, the data structure was organized in hierarchical layers to categorize information with increasing levels of detail from the Layer 0 down to more specific categories and sub-categories, as shown in Figure 2. The breakdown structure is defined as follows.
Layer 0: Region. It is the top layer. It indicates a broad geographical categorization, such as a geographical region or CH site area.
Layer 1: Sacro Monte. The layer specifies a category that refers to a specific example of a cultural or religious site within the region, such as a sacred mountain or pilgrimage complex.
Layer 2: Building. This layer drills down to specific buildings within the site category.
Layer 3: Architectural Element. Further detailing occurs at this layer, focusing on architectural elements of the buildings, referring to distinctive architectural features or components.
Layer 4: Object. In MDS, the most granular level of data is referred to as a "member." Members are the actual data records stored within the MDS system. They represent the specific instances of master data defined by the model. Members can be considered the individual rows within a table in traditional database terms. These members hold the details relevant to each specific architectural element, such as its unique identification code, description, and any other attributes defined for the entity.
MDS supports various attribute types that allow for the detailed modeling of entities within its framework. These attributes can be broadly categorized into the following types:

1. Numeric attributes that store numerical values, which can be integers or decimals, are helpful for quantitative data, such as weights or dimensions.
2. Text attributes that include strings can contain letters, numbers, and other characters, codes, descriptions, or other alphanumeric information.
3. DateTime attributes enable tracking temporal information like creation and modification dates and other time-related data critical for historical records or scheduling.
4. Domain-based attributes are used to reference other entities within MDS, creating a relationship between them, acting similarly to foreign keys in relational databases, ensuring referential integrity and enabling hierarchical structuring of master data.
5. File attributes to store binary data, such as images or documents, directly linked to a master data entity.
6. Boolean attributes for true/false or yes/no values, valid for flags or binary decisions associated with an entity.
7. Web Link attributes store URLs of external contents, such as external websites or datasheets.

This set of attribute types enables a rich and nuanced representation of any data, allowing the design of comprehensive models that accurately reflect the multifaceted nature of their architectural elements. In MDS, entity-based attributes play a crucial role in structuring and pivoting members into different hierarchies. These attributes, which define the characteristics or properties of an entity, can be used as pivot points to create multiple hierarchical views (Figure 4). By associating members with specific attributes, MDS allows for the dynamic organization of data into hierarchies that reflect the various dimensions of data organization. For instance, an architectural element entity member could be associated with attributes such as category. This attribute can then be used to pivot the same elements into a category-based hierarchy. This flexibility is essential for tailoring views and reports to the specific needs of different CH operational contexts, enabling users to analyse and manage master data from multiple perspectives while maintaining a single version of the truth within the MDS environment. The possibility of tracking the changes for the member attributes in MDS is a pivotal feature that ensures the integrity and history of CH data over time (Figure 3). Whenever an attribute of a member is added, modified, or deleted, MDS records and preserves each change. This historical tracking is vital for auditing purposes, enabling maintenance teams to see when a change was made, who made it, and the details of the modification. This feature facilitates compliance with various regulatory standards by providing a transparent trail of data modifications. Additionally, this capability supports data stewards in managing the lifecycle of the CH data estate and identifying with an overview the trends or patterns in data changes and reverting to previous states if necessary. The change tracking system can also be configured to trigger workflows or notifications, ensuring that relevant stakeholders are informed of important changes as they occur.This granular level of control and oversight is crucial to maintaining the quality and reliability of master data within an organization, providing a solid and reliable foundation for maintenance and inspection processes.
The attribute change tracking described previously enables "version control", a critical capability that allows logging different versions of CH models over time. Each model in MDS can have multiple versions: this enables the management and preservation of snapshots of the master data at various points in time. This functionality is particularly useful for tracking historical data, testing changes, and determining their effects on a "safe environment" before applying them to the actual environment or rolling back to previous versions if needed. Version management supports a collaborative approach where changes can be reviewed and approved before they become part of the published record. Each version can be locked to prevent further changes, unlocked for additional edits, or committed to finalize the changes. The MDS system provides a clear, trackable, and auditable trail of how master data has evolved,

ensuring that any alterations are traceable and reversible, enhancing data governance and integrity within the different iterations.

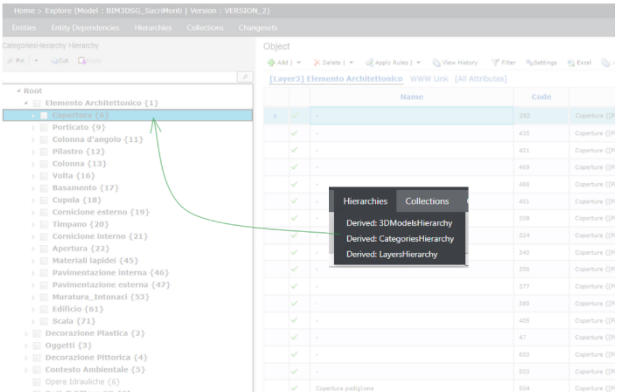

Figure 4. Derived models from a category of architectural elements

The Excel add-in for MDS enhances the user experience by leveraging the familiar environment of Microsoft Excel to manage CH data. This add-in includes a number of features that make it easier for data stewards to engage with their platform. Users can connect directly to MDS databases and work with the data as they would in a conventional Excel spreadsheet, complementing the operations performed through the online web interface. This includes sorting, filtering, and analysing master data. They can also use the add-in to create new entities, add members, and validate data against the rules defined in MDS. Moreover, the add-in enables bulk updates, which is particularly useful for making large-scale changes or updates to the data.
The Excel interface simplifies the process of publishing data back to the MDS repository with few clicks, ensuring that all changes are synchronized with the central master data. Additionally, the add-in supports version management, allowing users to work with different versions of the data and access to the history of changes. This integration between MDS and Excel streamlines master data management processes, making it more accessible and efficient.

5. CONCLUSIONS

This research has demonstrated that a challenging case study of cultural heritage, such as Sacri Monti's, necessitates the implementation of a specific methodology and the utilisation of specialised instruments to facilitate the demanding maintenance tasks. The challenges raised by the CH complexity seems not to be addressed by a unique answer, but to require dedicated methods and adaptable instruments, that can be adapted to the specific case study and to maintenance practice, as well as to the available data and resources. The web platforms dedicated to Sacri Monti described in this article testify this diversity of approach. The problem of the 3D models that support the information in BIM-like frameworks it is a significant effort in terms of time and need of interpretation by the modelling operator. The possibility of using point clouds instead of BIM models is promising but not effortless, as it requires post-acquisition processing and semantic classification in order to be proficiently used in an information system oriented towards the architectural objects. Moreover, point clouds and other products of reality capture need to be supported by the information system in use. The paper proposes a novel data-driven approach to the management of the data in the field of CH maintenance and conservation. The MDM framework is well-established among enterprises and in the IT sector and proved to be effective and crucial in improving data quality and implementation of data governance policies. From this consideration it descends the main idea of applying the MDM framework and its dedicated instruments as MDS to the field of CH management.
The available tools in MDS and its ability to manage complex datasets and their relations are fundamental in developing a Minimum Viable Product (MVP) web platform able to support the programmed maintenance process of a complex CH asset such as the Sacri Monti. Moreover, the MDM framework is focused on data quality and information consistency, which are the main requirements for establishing the Master Data Record. The possibility of using, according to the need, a double editing tool, the web interface and the MS Excel add-in is a significant feature that eases the operators' use, relying on widespread and stable software. Moreover, MDS eases data exporting and integration with other platforms, ensuring the interoperability of data and its structure. Finally, the MDM framework embeds auditing and logging practices that make the data resilient and prevent unwanted losses and alterations, a key feature of the archival perspective of the information concerning the conditions of the common architectural heritage.

ACKNOWLEDGEMENTS

The authors want to acknowledge the "Ente Di Gestione Sacri Monti" for providing the technical and historical data.

REFERENCES

Achille, C., Tommasi, C., Rechichi, F., Fassi, F., De Filippis, E., 2019. Towards an Advanced Conservation Strategy: a Structured Database for Sharing 3D Documentation Between Expert Users. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-2/W15, 9–16. https://doi.org/10.5194/isprs-archives-XLII-2-W15-9-2019

Acosta, E., Spettu, F., Fiorillo, F., 2022. A procedure to import a complex geometry model of a Heritage Building into BIM for advanced architectural representations. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLVI-2/W1-2022, 9–16. https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-9-2022

Autodesk, 2024. Autodesk Platform Services (formerly Forge). https://aps.autodesk.com/ (accessed 1.12.24).

Autodesk, 2023. Autodesk. https://www.autodesk.eu (accessed 1.14.24).

Bruno, N., Rechichi, F., Achille, C., Zerbi, A., Roncella, R., Fassi, F., 2020. Integration of historical GIS data in a HBIM system. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLIII-B4-2020, 427–434. https://doi.org/10.5194/isprs-archives-XLIII-B4-2020-427-2020

Cintoo, 2024. Cintoo Cloud. https://cintoo.com/ (accessed 1.15.24).

Colucci, E., Iacono, E., Matrone, F., Ventura, G.M., 2023. The development of a 2D/3D BIM-GIS web platform for planned maintenance of built and Cultural Heritage: the Main10Ance Project. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci XLVIII-M-2–2023, 433–439. https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-433-2023

Ente di gestione dei Sacri Monti, 2024a. Projects and restorations. https://www.sacrimonti.org/en/i-progetti-e-restauri#/?pag=1&num=10&qry=progettierestauri&so=score%20desc&view=list&p1=&p2=&kw= (accessed 1.16.24).

Ente di gestione dei Sacri Monti, 2024b. The Sacri Monti of Piedmont and Lombardy. https://www.sacrimonti.org/en/home (accessed 10.31.23).

Fassi, F., Achille, C., Fiorillo, F., Spettu, F., Parri, S., 2023. Bridging the gap between 3D survey and use of digital data in the CH field, in: Vileikis, O., Brown, S. (Eds.), ICOMOS GA2023 Book of Abstracts. ICOMOS International, Sidney, p. 331.

Fassi, F., Achille, C., Mandelli, A., Rechichi, F., Parri, S., 2015. A New idea of bim system for visualization, web sharing and using huge complex 3d models for facility management., in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives. https://doi.org/10.5194/isprsarchives-XL-5-W4-359-2015

Fiorillo, F., Spettu, F., 2023. Data management, efficient use, and smart access to reality capture data via web platforms, in: Picchio, F. (Ed.), Digital & Documentation. From Virtual Space to Information Database. Pavia University Press, Pavia, pp. 163–177.

Fleckenstein, M., Fellows, L., 2018. Master Data Management, in: Fleckenstein, M., Fellows, L. (Eds.), Modern Data Strategy. Springer International Publishing, Cham, pp. 93–99.

García-Valldecabres, J., Galiano-Garrigós, A., Meseguer, L.C., López González, M.C., 2021. HBIM work methodology applied to preventive maintenance: a state-of-the-art review. WIT Transactions on The Built Environment 157–169. https://doi.org/10.2495/BIM210131

Gartner Inc, 2023. Gartner Information Technology Glossary. Gartner. https://www.gartner.com/en/information-technology/glossary/master-data-management-mdm (accessed 1.15.24).

Geovast 3D, 2024. FlyVast. https://flyvast.com/ (accessed 1.15.24).

Lauer, C., 2021. What is a Data Hub?. Medium. https://towardsdatascience.com/what-is-a-data-hub-41d2ac34c270 (accessed 1.15.24).

Lovell, L.J., Davies, R.J., Hunt, D.V.L., 2023. The Application of Historic Building Information Modelling (HBIM) to Cultural Heritage: A Review. Heritage 6, 6691–6717. https://doi.org/10.3390/heritage6100350

Main10ance, 2024. Main10ance Viewer Demo. https://main10ance-app-demo.onrender.com/ (accessed 1.12.24).

Main10ance, 2023. MAIN10ANCE – Valorizzazione del patrimonio naturale e culturale. https://main10ance.eu/ (accessed 1.12.24).

Maravelakis, E., Konstantaras, A., Kritsotaki, A., Angelakis, D., Xinogalos, M., 2013. Analysing User Needs for a Unified 3D Metadata Recording and Exploitation of Cultural Heritage Monuments System, in: Bebis, G., Boyle, R., Parvin, B., Koracin, D., Li, B., Porikli, F., Zordan, V., Klosowski, J., Coquillart, S., Luo, X., Chen, M., Gotz, D. (Eds.), Advances in Visual Computing, Lecture Notes in Computer Science. Springer, Berlin, Heidelberg, pp. 138–147. https://doi.org/10.1007/978-3-642-41939-3_14

Matrone, F., Colucci, E., Iacono, E., Ventura, G.M., 2023. The HBIM-GIS Main10ance Platform to Enhance the Maintenance and Conservation of Historical Built Heritage. Sensors 23, 8112. https://doi.org/10.3390/s23198112

Microsoft, 2023. Overview - SQL Server Master Data Services. https://learn.microsoft.com/en-us/sql/master-data-services/master-data-services-overview-mds?view=sql-server-ver16 (accessed 10.27.23).

Open Source Geospatial Foundation, 2024. GeoServer. https://geoserver.org/ (accessed 1.14.24).

PostGIS PSC, 2024. PostGIS. PostGIS. https://postgis.net/ (accessed 1.14.24).

PostgreSQL Community, 2024. pgAdmin - PostgreSQL Tools. https://www.pgadmin.org/ (accessed 1.14.24).

PostgreSQL Global Development Group, 2024. PostgreSQL. PostgreSQL. https://www.postgresql.org/ (accessed 1.14.24).

Rechichi, F., 2020. Chimera: a BIM+GIS system for Cultural Heritage. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLIII-B4-2020, 493–500. https://doi.org/10.5194/isprs-archives-XLIII-B4-2020-493-2020

Spettu, F., Teruggi, S., Canali, F., Achille, C., Fassi, F., 2021. A hybrid model for the reverse engineering of the Milan Cathedral. Challenges and lesson learnt, in: Proceedings ARQUEOLÓGICA 2.0 - 9th International Congress & 3rd GEORES - GEOmatics and pREServation. Editorial Universitat Politécnica de Valéncia. https://doi.org/10.4995/arqueologica9.2021.12138

Stedman, C., Vaughan, J., 2023. What is Master Data Management (MDM) and Why is it Important?. https://www.techtarget.com/searchdatamanagement/definition/master-data-management (accessed 1.18.24).

Teruggi, S., Fassi, F., 2021. Machines Learning for Mixed Reality. The Milan Cathedral from Survey to Holograms, in: Pattern Recognition. ICPR International Workshops and Challenges. ICPR 2021. p. 15.

Tommasi, C., Achille, C., Fanzini, D., Fassi, F., 2020. Advanced Digital Technologies for the Conservation and Valorisation of the UNESCO Sacri Monti, in: Daniotti, B., Gianinetto, M., Della Torre, S. (Eds.), Digital Transformation of the Design, Construction and Management Processes of the Built Environment, Research for Development. Springer International Publishing, Cham, pp. 379–389.

UNESCO, 2023. World Heritage List, Sacri Monti of Piedmont and Lombardy. https://whc.unesco.org/en/list/1068 (accessed 10.30.23).

Yang, X., Grussenmeyer, P., Koehl, M., Macher, H., Murtiyoso, A., Landes, T., 2020. Review of built heritage modelling: Integration of HBIM and other information techniques. Journal of Cultural Heritage 46, 350–360. https://doi.org/10.1016/j.culher.2020.05.008

Zerbinatti, M., Grazzini, A., Sara, F., Vercelli, G., 2023. The timber roof structure of Chapel XVI at Sacro Monte of Orta: an example of conservative strengthening work. Rivista Tema SI. https://doi.org/10.30682/tema08SIp

Zerbinatti, M., Matrone, F., LINGUA, A., 2021. Planned maintenance for architectural heritage. Experiences in progress from 3D survey to intervention programmes through HBIM. Rivista Tema Vol. 7. https://doi.org/10.30682/tema0701d

Zhang, K., Teruggi, S., Fassi, F., 2022. Machine Learning methods for UNESCO Chinese Heritage: complexity and comparisons. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLVI-2-W1-2022, 543–550. https://doi.org/10.5194/isprs-archives-XLVI-2-W1-2022-543-2022